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14. ABSTRACT The objectives of this project are <ul style="list-style-type: none"> To investigate the limits of empirical matched field processing and other coherent array detection and parameter estimation methods as receiver aperture size increases from a few kilometers to many hundreds of kilometers. To investigate techniques for extending the geographical source-region footprint over which empirical matched field processing and other coherent calibrated methods apply. Under a previous contract, we demonstrated the ability of empirical matched field processing to classify mining explosions by originating mine, using data from a single small-aperture array (ARCES) applied to mining events on the Kola Peninsula. In the current contract, we have chosen central Asia as our study region to assure programmatic relevance and to exploit the large belts of natural and man-made seismicity required for a test of our processing strategy. Data from suitable networks available for the study are from the four Kazakhstan arrays (MKAR, KKAR, ABKAR, BRVK) and the Kyrgyzstan network. Our overall approach will be to start with small apertures (the individual Kazakhstan arrays considered separately) to check the reproducibility of results we obtained for the European Arctic, then to extend the processing strategy first to a medium aperture (the Kyrgyzstan network; 200 km aperture) and then a large aperture (the four Kazakhstan arrays considered as a single coherent aperture; >1000 km). Simultaneously we will investigate methods to expand the source region footprint over which calibrations for coherent methods apply. We have expanded our work on the dataset of mining explosions in the Kola Peninsula to investigate further the potential of the method and to validate the preliminary results obtained under a previous contract (BAA03-27). This validation has consisted of analyzing several hundred seismic waveforms from available local stations (Apatity and Lovozero) to make additional checks on the original ground truth information provided by the mining authorities. Cross validation also was introduced to avoid circularity in the data analysis. Through the use of empirical matched field processing we were able correctly to classify 539 of 549 explosions by originating mine among 10 closely spaced mines, using short segments (<10 seconds, filtered in the 2.5–12.5 Hz band) of Pn waves observed at the ARCES array. The mines are separated by as little as 3 kilometers and observed at a 340–410 kilometer range. Such classification performance is far superior to that obtained by traditional methods. Matched field processing should find application in screening mining explosions in Comprehensive Nuclear-Test-Ban Treaty monitoring applications and in studies of natural seismicity.				
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**EXPANDING COHERENT ARRAY PROCESSING TO LARGER APERTURES USING
EMPIRICAL MATCHED FIELD PROCESSING**

Frode Ringdal¹, David B. Harris², Tormod Kværna¹, and Steven J. Gibbons¹

NORSAR¹ and Lawrence Livermore National Laboratory²

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ABSTRACT

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OBJECTIVES

The objectives of this project are

- To investigate the limits of empirical matched field processing and other coherent array detection and parameter estimation methods as receiver aperture size increases from a few kilometers to many hundreds of kilometers.
- To investigate techniques for extending the geographical source-region footprint over which empirical matched field processing and other coherent calibrated methods apply.

We will begin by reanalyzing data from the European Arctic in order to reconfirm the potential of empirical matched field processing that has been indicated by our work under a previous contract. We then will proceed to study the central Asia region to assure programmatic relevance and to exploit the large belts of natural and man-made seismicity to test the applicability of the technique to diffuse seismicity.

RESEARCH ACCOMPLISHED

Introduction

Current operational seismic array processing methods for detection (beamforming) and parameter estimation (frequency-wavenumber analysis) have changed little since their introduction in the 1960s and 1970s. These methods rely upon a plane-wave assumption for predicting the spatial amplitude and phase structure of seismic waves incident upon an array aperture. Scattering and refraction in strongly heterogeneous seismic propagation media constrain the size of usable coherent processing apertures under the plane-wave assumption to a few wavelengths. This constraint severely limits the spatial resolution of beamforming and frequency-wavenumber (F-K) methods. In addition, the spatial correlation of ambient seismic noise constrains the minimum usable element separation. The combination of these constraints bounds the maximum number of usable sensors and places a fundamental limit on coherent processing gain through beamforming.

Existing beamforming and F-K estimation methods make some attempt to compensate for the non-ideal spatial structure of seismic waves. For example, it is common to apply an amplitude correction to estimated spatial covariance matrices when using the indirect approach to F-K spectrum estimation (i.e., by estimating the spatial covariance function first, then evaluating its Fourier transform to obtain a wavenumber spectrum). Each element of the matrix is normalized by the square root of the diagonal elements in the same row and column. In direct methods (e.g., Kverna and Ringdal, 1986), it is now standard to integrate the F-K spectrum over a band of frequencies to stabilize the narrowband estimates that individually have high variance. That variance is controlled, in part, by the very small time-bandwidth product of signals in short analysis windows. However, it is likely that variance in the F-K estimate from frequency to frequency also is a function of wavefield scattering.

Recent advances in standardization of analysis windows and frequency bands for particular source regions have produced dramatic reductions in the variance of azimuth/slowness estimates derived from F-K spectra (Gibbons et al., 2005), at least in frequency bands (below 6–8 Hz) where the wavefield is approximately coherent across regional-array apertures. Finally, it is common to apply post-processing (i.e., post-F-K) vector slowness corrections (Schweitzer, 2001) to azimuth/slowness measurements in an attempt to remove frequency-dependent biases caused (presumably) by unmodeled wavefield refraction.

Recently, detection algorithms that exploit aperture-level calibrations have been developed that often substantially reduce detection thresholds in beamforming operations. Correlation detectors (Gibbons and Ringdal, 2006) and subspace detectors (Harris, 2006) use previously observed waveforms from events at specific sources in sensitive algorithms to detect subsequent events at those same sources. These algorithms rely upon the fact that the temporal and spatial structures of signals from these sources often are repeatable; past events constitute a spatio-temporal calibration across an array or network of sensors for future events. Such detectors simultaneously detect, locate, and identify events as being consistent with previous events at the same source location, with the same source time history and mechanism.

However, while the full exploitation of the spatial and temporal structure of the signal frequently leads to detectors one to two orders of magnitude more sensitive than simple power detectors (with conventional beamforming), such exploitation also presents two barriers to widespread application. Correlation methods generally have a source-region geographic footprint one to two wavelengths across (Harris, 1991), which can be ameliorated to some extent with the more general waveform representation of a subspace detector (Harris, 2006). Correlation methods correct incoherence across the receiver aperture, but trade it for incoherence across the source region; the reciprocity principle is at play in the correlation detection strategy. Correlation methods also are sensitive to source mechanism and time history, and can fail when these attributes differ from event to event.

The sensitivities of F-K methods and conventional beamforming to the plane wave assumption and of correlation methods to source variability leads us to consider another processing strategy based on temporally-incoherent, but spatially coherent signal processing extended with subspace techniques. Our general approach is to adapt narrowband empirical matched field processing, originally conceived for underwater acoustic applications (Baggeroer et al., 1993; Fialkowski et al., 2000) to the seismic monitoring task. Our processing agenda consists of (1) breaking the observed signal into narrow bands, (2) using empirical matched field methods to combine the near-monochromatic resultant waveforms coherently across an aperture to achieve processing gain, and (3) integrating the resulting power incoherently over the narrow bands to achieve a wideband result. We anticipate that this approach will ameliorate variations in source time history from event to event that defeat waveform correlation methods.

Matched field processing derives its name from the realization that conventional narrowband beamforming is a spatial matched filtering operation for plane waves, and that more general forms of spatial matched filtering are possible. In underwater acoustics, the velocity structure of the medium is far less variable than the seismic propagation medium and frequently known in detail. In such circumstances, it is possible to compute the detailed phase and amplitude structure of a narrowband wavefield incident on an array and apply the computed structure as the focusing kernel in a beamforming operation. This approach works well in the SOund Fixing And Ranging (SOFAR) channel waveguide and allows coherent processing across arrays to be expanded beyond the physical aperture limits implied by the assumption of a planar structure (locally the field is planar). A clever empirical approach to estimating the structure of the narrowband acoustic wavefield directly from observed wavefields was attempted (Fialkowski et al., 2000) but largely failed because of the spatial nonstationarity of the source.

Reanalyzing Mining Data from the European Arctic

Under a previous contract, DE-FC52-03NA99517 (Kværna et al., 2007), we demonstrated the ability of empirical matched field processing to classify mining explosions by originating mine, using data from a single small-aperture array (ARCES) applied to mining events on the Kola Peninsula.

We have continued our work on this data set for the mining explosions at the Kola Peninsula in order to further validate the preliminary results summarized by Kværna et al. (2007). This validation has consisted of analyzing over 500 seismic waveforms from available local stations (Apatity and Lovozero) to make additional checks on the original ground truth information provided by the mining authorities. We have also carried out classification tests using cross-validation to avoid issues of circularity.

We study the European arctic region (Figure 1) where the ARCES array, located in northern Norway, is 340–410 kilometers from two groups of mines in the Kola peninsula, Russia: the Olenegorsk (O1-O5) and Khibiny (K1-K5) groups. In monitoring for signals from distant nuclear events, the array observes thousands of mining explosions annually, which can be screened if attributed with a high level of confidence to their originating mines. However, the array, with a 3-kilometer aperture, is too small to resolve the individual mines. The array resolution (Rayleigh criterion) is determined by the separation of half-power (3 dB) points of the main lobe of the array wavenumber response. In Figure 1, the 3 dB points of the array response (at 4, 8, and 12 Hz) for first-arriving Pn waves are projected onto the array's geographic field of view; the array has been steered to one particular mine (K2). All 10 mines fall within the 3 dB contours even at 12 Hz.



Figure 1. The mines of the Khibiny and Olenegorsk regions are too close for explosions to be attributed to specific mines on the basis of wavenumber (F-K) spectrum direction estimates made from ARCES array (upper left) observations of Pn waves (Figure 2). ARCES resolution is indicated on the map at lower left, which shows the half-power contours of the array response at three frequencies when the array is steered to the Rasvumchorr mine (K2).

We consider separating explosions from the 10 mines using only the first-arriving Pn wave. Figure 2 displays ARCES center station observations of 37 explosions originating at the Norpakh mine (K5). Note the large degree of signal variation, which complicates the use of correlation methods. For our analysis, we selected 549 explosions attributed to specific mines using reports from the mine operators, validated with data from stations (APA, LVZ) local to the mines.

The classical technique for estimating incident wave velocity and direction is the F-K spectrum,

$$P(\omega, \vec{k}) = \left| \int dt \sum_j r(t, \vec{x}_j) e^{i(\omega t - \vec{k} \cdot \vec{x}_j)} \right|^2 = \vec{\varepsilon}^H \vec{R}(\omega) \vec{\varepsilon} \quad (1)$$

which maps the energy incident upon the array as a function of frequency ω and wavenumber (direction) \vec{k} by computing a multidimensional Fourier transform of the signals $r(t, \vec{x}_j)$ recorded at the sensor locations \vec{x}_j . The F-K spectrum can be written as the indicated quadratic form between the steering vector

$\vec{\varepsilon} = \begin{bmatrix} e^{-i\vec{k} \cdot \vec{x}_1} & \dots & e^{-i\vec{k} \cdot \vec{x}_N} \end{bmatrix}^T$, which expresses the spatial phase and amplitude structure of incident monochromatic plane waves, and the spatial covariance matrix \vec{R} , containing the cross-spectral information $R_{mn}(\omega) = (\int r(t, \vec{x}_m) e^{-i\omega t} dt)(\int r(t, \vec{x}_n) e^{i\omega t} dt)$ among the sensor waveforms.

Figure 2. The ensemble of events used to calibrate the Norpakh mine (K5). Note that the first-arriving P waves (see inset) show a degree of variation that makes classification by waveform correlation methods infeasible.

It is common to integrate the energy over frequency to produce a map of total incident energy as a function of vector slowness, \vec{s} ,

$$\hat{P}(\vec{s}) = \int P(\omega, \omega \vec{s}) d\omega \quad (2)$$

This function aggregates energy incoherently across frequency, which is the basis for wideband estimation algorithms not sensitive to the specific temporal structure of signals.

The direction to the source of an observed signal is estimated by maximizing $\hat{P}(\vec{s})$ over vector slowness. In practice, the wavefield often is strongly refracted leading to significant bias in direction estimates. It is common to compensate refraction effects with empirical corrections to the estimated slowness derived from events of known location (Schweitzer, 2001). This calibration approach effectively replaces the theoretical steering vector for a particular direction and velocity with a corrected vector, although one that still conforms to a plane wave signal.

Improvements in estimation accuracy result from improving the representation of the incident wavefield structure, embodied in the steering vectors. In underwater sound localization problems, matched field processing (Baggeroer et al., 1993) maximizes the quadratic form of Equation (1) over a manifold of steering vectors computed from detailed models of the oceanic sound velocity profile (SVP). Sufficiently accurate SVP models are not always available, which motivated attempts to develop steering vectors empirically (Fialkowski et al., 2000). In hydroacoustic applications, signal sources frequently are ships producing continuous waveforms modeled as narrowband random processes. When a single source is present, the steering vectors are obtained as the principal eigenvectors of sample covariance matrices estimated from array observations of the continuous wavefield.

In adapting the matched field processing approach to seismic applications, an empirical approach is required, since geophysical models of the propagation environment (the Earth) are not sufficiently detailed or accurate to predict wavefield structure, except at very low frequencies ($< \sim 0.1$ Hz). We are interested in improving performance at frequencies as high as 12 Hz. Since the typical seismogram consists of many different waves propagating in a multipath environment, we limit the observation window to a small portion of the waveform (approximately the first ten seconds) where we can be reasonably sure that a single wave is present. The short window raises the question of how to obtain suitably stable estimates of spectral covariance matrices. We solve this problem by assembling ensembles of events, such as that shown in Figure 2, from repeating sources (mines). The covariance matrices are computed as the ensemble average.

To provide a baseline for array performance consistent with the classical resolution limit, we classify the 549 explosions by originating mine first by maximizing $\hat{P}(\vec{s})$ over the 10 plane-wave steering vectors appropriate to the great-circle azimuths to the mines. We refer to this approach as theoretical plane-wave (F-K) classification. We also perform the classification with calibrated plane-wave steering vectors, for which the directions and velocities have been chosen to maximize the ensemble power for each mine. We refer to this approach as empirical plane wave classification. Finally, we perform matched field classification using steering vectors obtained as the principal eigenvectors of the ensemble covariance matrices. In all cases, we estimate the energy in the 2.5–12.5 Hz frequency band, discretizing this band into 33 subbands of 0.3125-Hz width for the covariance calculations. We use a cross-validation approach to avoid circularity in the estimation process.

The three algorithms represent different choices for representing the narrowband spatial structure of the incident wavefield under the 10 source hypotheses. To assess the quality of the representations, we measure the normalized energy

$$\frac{\sum_j \vec{e}_j^H \bar{R}(\omega_j) \vec{e}_j}{\sum_j \text{tr}\{\bar{R}(\omega_j)\}} \quad (3)$$

which ranges between 0 and 1 and is 1 only if the steering vectors represent 100% of the signal energy incident on the array. It is the fraction of energy captured by the specific representation.

Energy capture for one mine, Olenegorsk, under the 10 source hypotheses is shown in Figure 3. Both plane-wave classification methods have energy capture distributions centered about 0.2–0.3 for Olenegorsk events under the Olenegorsk origin hypothesis. The energy capture for the alternative hypotheses, which ideally should be 0, is lower for the empirical plane wave classifier than its theoretical counterpart, suggesting better classification performance for the calibrated classifier. Distributions for the matched field method show a very wide spread between the Olenegorsk hypothesis, for which energy capture averages about 0.8, and alternate hypotheses, predicting a high classification success rate.

Figure 3. Distributions of the matched field processing classification statistic (right) for the Olenegorsk (O2) mine population of 52 events under the 10 hypotheses about originating source (indicated at left) separate O2 unambiguously from the other mines. Frequency distributions for the theoretical plane-wave F-K classifier (left) are ambiguous. Distributions for the empirical plane wave F-K classifier show slightly improved separation between the two mining groups.

Histograms of the relative frequency of classification for events from each mine obtained by maximizing $\hat{P}(\vec{s})$ under the 10 hypotheses are shown in Figure 4. In the theoretical plane-wave case, a single mine, Rasvumchorr (K2), is assigned most of the events. Observed Pn azimuths generally are biased clockwise (to the south) for most events in this region. The Rasvumchorr mine is the southernmost mine, consequently the theoretical steering vector for this mine presents the best fit to the refracted wavefields. The empirical plane-wave classifier performs considerably better, generally assigning Olenegorsk group events to Olenegorsk mines and Khibiny events to Khibiny mines, probably as a consequence of calibrating wideband refraction effects. However, the empirical plane-wave classifier has large error rates when distinguishing among the 5 mines in each group. By contrast the matched-field classifier achieves nearly complete separation of the mines (1.8% misclassification rate).